REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
FINAL REPORT - 01 Dec 94 - 30 Nov 96

4. TITLE AND SUBTITLE
BASIC RESEARCH IN MICROWAVE-PLASMA INTERACTION

5. FUNDING NUMBERS
61102F
2301/ES

6. AUTHOR(S)
Professor Spencer Kuo

AFOSR-TR-97
0164

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Polytechnic University
Farmingdale, NY 11735

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-94-1-0076

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The investigation covered by the grant includes three research areas: (1) Development of a microwave tube called "cuspton" which converts the kinetic energy of a relativistic electron beam (e-layer) into microwaves by resonant interaction at a cyclotron harmonic with the mode field of a sixteen slot waveguide, (2) study of microwave plasma interaction for the application of high power microwaves and plasma cloaking, focused on using a fast space-time varying plasma to modify the propagation characteristics and spectral content of the interacting microwave, and using a periodically structured plasma to enhance wave scattering, and (3) nonlinear effect of large amplitude waves on the trajectory of charged particles.

19970602 034

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Technical ~~Annual~~ Final Report on Air Force Office of Scientific Research
Grant AFOSR-F49620-94-0076

(December 1, 1995 - November 30, 1996)

"Basic Research in Microwave-Plasma Interaction"

S.P. Kuo
Principal Investigator

Joe Huang
John Kim
James Faith
Ruthie Lyle
Ed Koretzky

Post Doctoral and Graduate Students

Weber Research Institute
Polytechnic University
Farmingdale, NY 11735

I. Introduction

The present report summarizes the work that has been carried out during the funding period Dec. 1, 1995 - Nov. 30, 1996 under the support of the AFOSR Grant AFOSR-F49620-94-0076.

The investigation covered by the Grant includes three research areas: (1) Development of a microwave tube called "cusptron" which converts the kinetic energy of a relativistic electron beam (e-layer) into microwaves by resonant interaction at a cyclotron harmonic with the mode fields of a sixteen slot waveguide, (2) study of microwave plasma interaction for the application of high power microwaves and plasma cloaking, focused on using a fast space-time varying plasma to modify the propagation characteristics and spectral content of the interacting microwave, and using a periodically structured plasma to enhance wave scattering, and (3) nonlinear effect of large amplitude waves on the trajectory of charged particles.

The research effort in each subject has been making good progress. The cathode (electron gun) of the cusptron device purchased two years ago has been operating properly. Our preliminary experimental results indicate that the best performance of the tube can be achieved by operating the tube at fifteenth harmonic TE_{12} peniotron mode, this being our primary focus. The magnetic field is just realigned to improve the cusp transition, and thus the quality of the e-layer. The experiments on frequency scattering of microwave by a rapidly time varying plasma has been conducted in two different steps. One is conducted in a rectangular Plexiglas chamber (3'×1.5'×1.3'). The plasma in the chamber is generated by a 60 kV dc discharge between the electrodes which consist of a spatially periodic array of parallel pairs of conducting plates. The discharge voltage is provided by a Marx capacitor bank, rated at 240 kV and 13 kJ maximum. The other one is conducted in a 2' cubic Plexiglas chamber. The plasma is generated by a microwave beam of 1 μs pulse length. A cw source is arranged to propagate through the fast growing plasma in the first one and the microwave pulse used to ionize background gas in the second one is also working as the diagnostic wave. The preliminary results of the experiment using the first setup show that the scheme of adding a spatially periodic feature to the fast growing dc discharge plasma can significantly enhance and broaden the frequency upshifting result in the output spectrum. The tradeoff of the scheme is to reduce the signal to

noise ratio, because the discharge current in a periodic structure becomes a more efficient radiator. Very broadband radiation generated by the discharge is detected. This leads us to have set up a new experiment to explore the possibility of developing a new source of wideband microwave pulse by synchronized dc discharge through a spatially periodic array of electrode pairs. The second experiment demonstrated that the microwave pulse self generated plasma can cause both upshift and downshift in the spectrum of the transmitted pulse. A thorough experiment to identify the cause of frequency downshift has been performed. Currently, we are carrying out numerical simulations based on the theoretical model developed in the previous work to reproduce the experimental results so that the experimental results can be explained without ambiguity. A Monte carlo simulation of the plasma dynamics is performed to study electron behavior in an electron cyclotron resonance (ECR) microwave discharge maintained by the TM_{11} mode fields of a plasma filled cylindrical waveguide. The time averaged, spatially dependent electron energy distribution (EED) is computed. It is shown that the TM_{11} mode fields are more effective for ECR interaction than the TM_{01} mode fields considered in the previous work. The produced plasma has a much larger mean electron energy and sheath potential, and is therefore more desirable for plasma processing applications. We have studied the scattering of electromagnetic wave by periodically structured plasma. It is based on the quasi-particle theory which is able to handle multiple scattering processes. The focus of the current analysis is on the effect of spectral bandwidth of the periodic perturbations to the wave scattering. The results show that 10% bandwidth can drastically reduce the net effects of multiple scattering. We have studied the interaction between a bouncing electron and a large amplitude whistler wave in the magnetosphere. It is shown that the trajectory of the electron can become chaotic.

II. Summary of Work Accomplished

A. Operation of cusptron tube at 15th harmonic TE_{12} peniotron mode of a sixteen slot waveguide.

A cusptron oscillator using a 16 slot waveguide for the generation of high cyclotron radiation is in operation. A radiation signal at 10 GHz is generated and has been matched to the 15 cyclotron harmonic corresponding to the 2π peniotron mode of the tube. Shown in Fig. 1 is a photograph recording the spectral distribution of the output signal. The e-beam energy and current are 16 kV and 0.5 A, respectively.

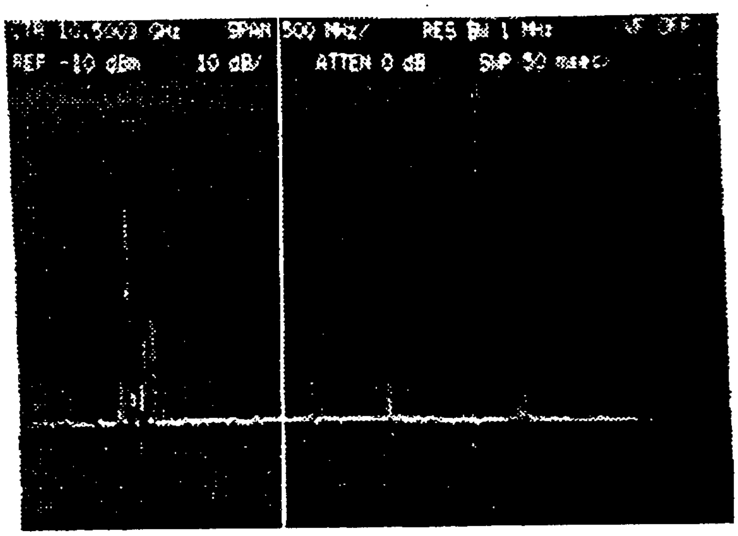

Fig.1 Spectrum analyzer trace of the three modes (π, peniotron, 2π)

B. Theory and simulation of peniotron modes excited in the cusptron.

Considering peniotron mode fields in the interaction region and including only the fundamental field components in the slot region, a dispersion relation for the peniotron mode is derived by imposing continuity conditions on the wave fields at the boundaries between the interaction and slot regions. Choosing the three peniotron modes (TE_{12} 2π, $TE_{15\ 1}$ 2π, and

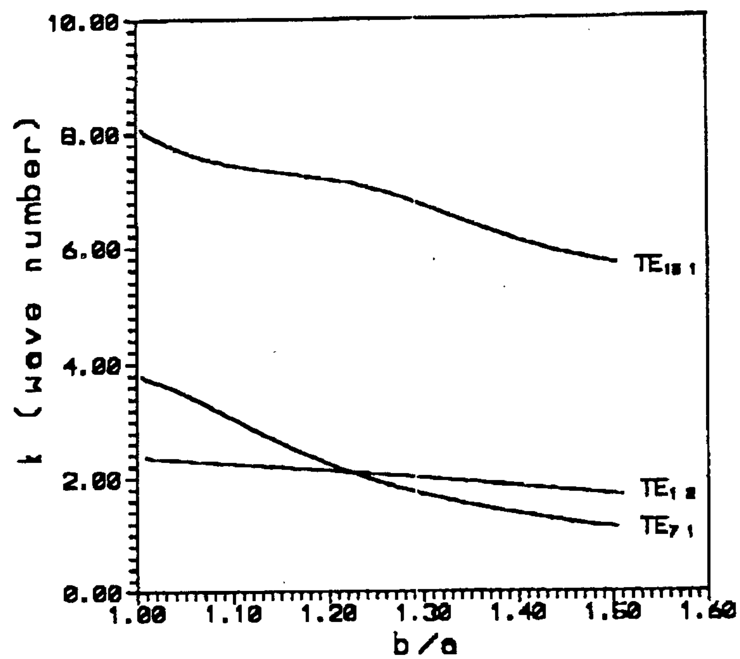

Fig.2 Functional dependence of wave number (k) on the ratio (b/a) of the outer to inner radii of the vane structure.

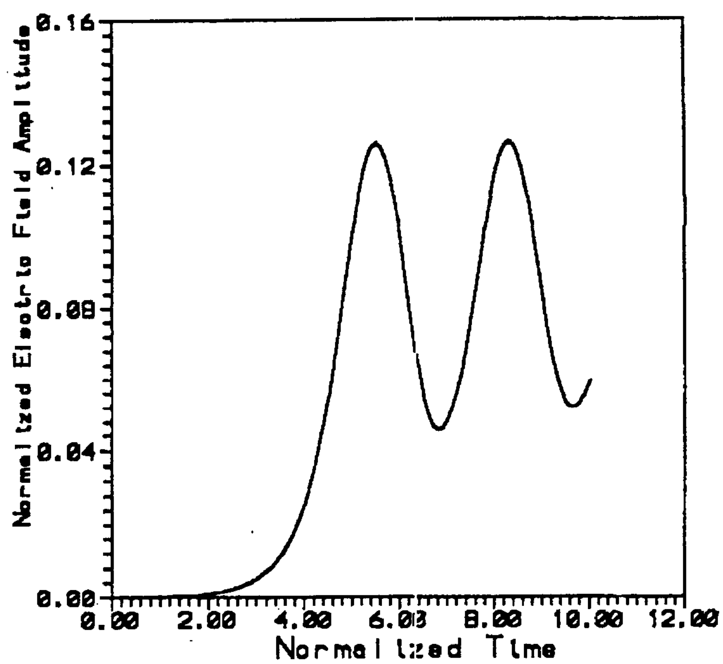

Fig.3 Temporal evolution of radiation field amplitude with $k=1.714\ cm^{-1}$, $\gamma_0=1.063$ of $TE_{7\,1}$ mode.

TE_{71} π modes) for the present analysis, the particle simulation code developed in our previous work is used to study the conversion efficiency of the kinetic energy of the e-layer into one of the three peniotron modes of the tube. In the particle simulation, a rotating e-beam has the constant line density of 1.6×10^{10} cm^{-1}. The cyclotron harmonic resonance relation $\omega = ck = N_0\Omega_0 / \gamma_0$ is used to simplify the particles' trajectory, where k is the wave number of the waveguide from the dispersion curve indicated in Fig. 2. Shown in Fig. 3 is a typical example of the temporal evolution of the wave field amplitude. The greatest field amplitude is subsequently used to determine the maximum conversion efficiency. The particle simulations provide the optimal operating parameters (i.e. electron beam energy, operating frequency, and magnetic field). The optimum design parameters and efficiencies of the three peniotron modes are summarized in table 1. The results show that our facility (less then 30 kV electron beams) is capable to operate at two peniotron modes (TE_{12} and TE_{71}).

mode	a	b	frequency	magnetic field	γ_0	efficiency
TE_{12}	1.98 cm	2.57 cm	9.72 GHz	235 Gauss	1.03	24.7%
TE_{71}	1.98	2.57	8.18	453	1.085	50.11%
TE_{15}	1.98	2.57	32.2	1280	1.676	4.1%

Table 1 Peniotron mode operating parameters.

C. Frequency Shift in a Rapidly Created Periodic Plasma

In the present work, we attempt to extend and improve upon the results obtained by our previous frequency shift experiments. As in the prior work, the experiment studies the conversion of a cw microwave into a frequency up-shifted and chirped pulse train using repetitive plasma discharge. However, the present experiment replaces the single solid electrodes with laminated plates with aluminum and copper placed alternately. Discharge between these periodically structured electrodes rapidly creates plasma layers, whose interaction with the cw wave provides the mechanism of frequency up-shift.

Our experiment is conducted inside rectangular box of 1" Plexiglas, with outer dimensions of approximately 36"×18"×16". Within the chamber we place the two parallel laminated electrode plates, which form an array of electrode pairs having a spatial period of 6 cm The size and spacing of the strips are chosen to shift the incident cw wave from 5 GHz to a 7.5 GHz output.

A C-band horn antenna is used to direct the incident cw microwave between the electrodes. In addition, we place a second C-band horn on the other side of the periodic electrode structure to observe the output spectrum with our HP 85698 spectrum analyzer. We create the plasma itself with a Marx capacitor bank discharge, operating at about 60 kV, which easily breaks down the low pressure gas (about 1 Torr) in the chamber.

Upon observation of the output spectrum after several discharges, we find a very broad band frequency shifted result. The component we observe with the greatest frequency shift resides at 8.5 GHz (a 55% shift), with additional components existing throughout the range between incident and maximum frequencies, with the results shown in Fig. 4. It is possible that components with even greater up-shift are present, but we have not, as yet, tried to detect them. In addition, evidence of significantly down-shifted components is also observed.

D. Generation of Wideband Microwave Pulse by Synchronized discharges Through an Array of Electrode Pairs

Most current high power microwave sources use free electrons in the form of beams as the radiation source. Recently, however, a new method involving the direct conversion of DC electric fields to radiation fields has come to light [Mori, et. al., PRL, 74, 562, 1995]. This new method uses an ionization front moving through a gas filled electrode array to produce an approximately sinusoidal static electric field. As the front passes an electrode pair, a burst of current, and thus a half cycle of radiation is produced. All the pulses then add coherently, giving a radiation field whose energy is derived directly from the dc electric field.

Our experiment consists of an S band rectangular waveguide, in which several (≥5) pairs of opposite placed holes are drilled. Through these holes are placed pairs of electrodes, between which a Marx capacitor bank is discharged. By adjusting the spacing of the electrodes, the first pair can be

CTR 6.0032 GHz   SPAN 500 MHz/   RES BW 100 kHz   VF OFF
REF -10 dBm   10 dB/   ATTEN 0 dB   SWP 10 sec/

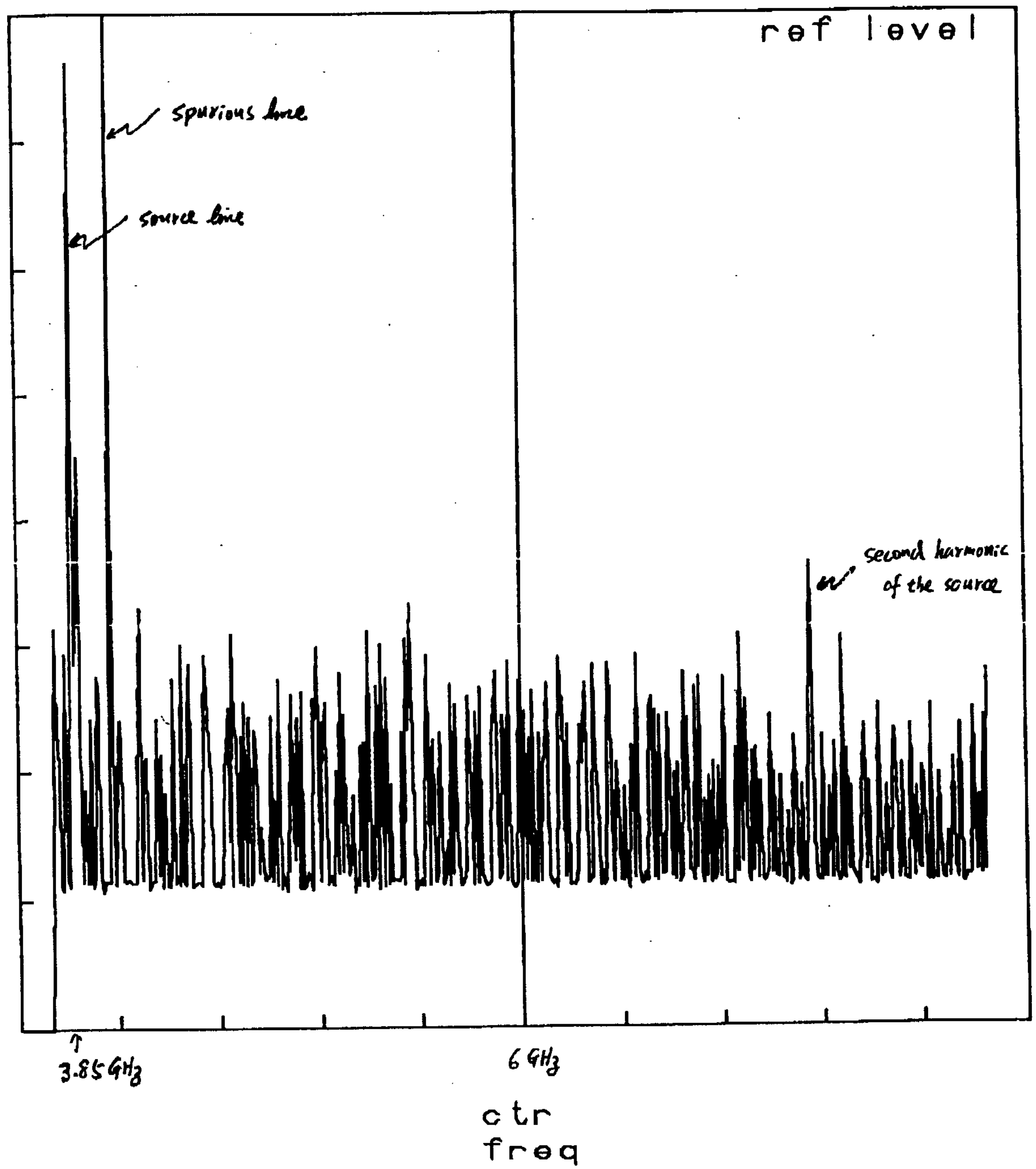

Fig. 4a Spectrum of up-shifted signal and radiation from the discharge

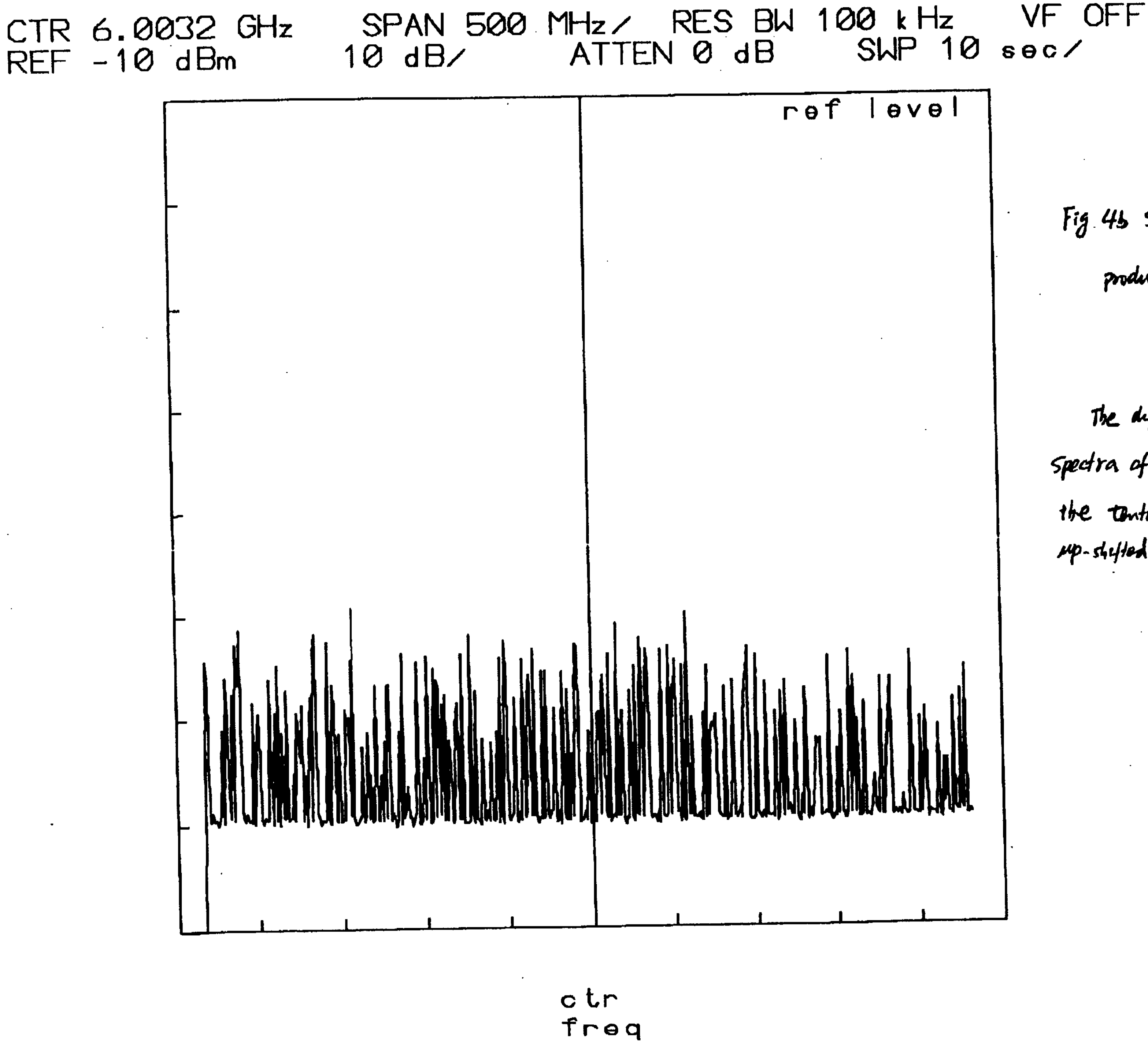

Fig 4b Spectrum of discharge produced radiation

The difference between the spectra of Figs 4a and 4b is the tentative spectrum of the up-shifted signal.

made to fire first. The resulting ultraviolet radiation from the spark preionizes the gas between the remaining electrodes, causing them to fire in sequence, and assuring that the microwave radiation pulses add coherently. This experiment is progressing. Moreover, the set up used in this experiment, described in C, has a periodic structure and can be used to test the idea. It is shown that the discharge can produce radiation peaked around 6.5 GHz. The result is presented in Fig. 5. The spectrum as shown is quite broad. This may be because the discharge is not quite synchronized, so the periodic feature can not impose a strong effect on the output signal.

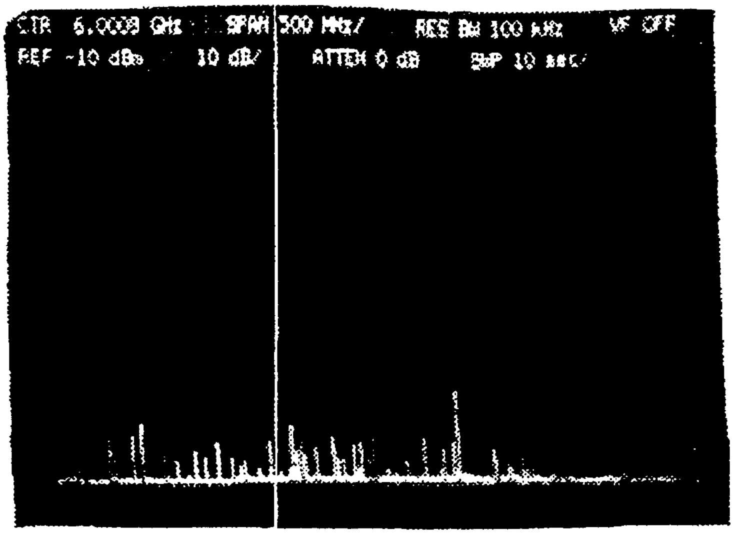

Figure 5. Radiation spectrum produced by the periodic discharge.

E. Frequency Downshift in Rapidly Ionizing Media

It is known that an electromagnetic wave propagating in a rapidly ionizing medium undergoes a frequency upshift. On the other hand, experimental results also indicate the simultaneous creation of a downshifted wave. A computer experiment was performed in our previous work by multiplying a variable parameter ξ to the electron-neutral collision frequency ν in the modal equations and varying ξ to demonstrate the role of ν in the frequency downshift result. In the present work, a thorough experiment devoted to identify the frequency downshift mechanism is performed. The results confirm the previous conclusion drawn by the computer experiment. More detailed information is provided in the appendix.

F. Chaotic Electron Motion Driven by Whistler Waves in the Magnetosphere Leading to Electron Precipitation into the Ionosphere

In the magnetosphere energetic electrons in the radiation belts are trapped by Earth's magnetic field. In the equatorial region where a symmetric mirror field may be assumed, there electrons undergo bounce motion along the lines of force. When a large amplitude whistler wave is present, the motion of the electrons is perturbed. The nonlinear interaction is shown to cause the motions of some of the trapped particles to become chaotic.

The chaoticity of the electron trajectory is determined by the two dimensional phase space portraits obtained by mapping the trajectory by surface of section techniques. The surface of section is applicable as the electron Hamiltonian can be transformed canonically into a time independent function. Shown in Figs. 6 ($p>0$) and 7 ($p<0$) are the portraits of the trajectory in the (z,p_z) space for the resonate case (i.e. the sum of the wave

G. Monte Carlo Simulation of Electron Behavior in an Electron Cyclotron Resonance Microwave Discharge Using Circular TM_{11} Mode Fields

Electron behavior in an electron cyclotron resonance (ECR) microwave discharge maintained by the TM_{11} mode fields of a plasma filled cylindrical waveguide has been investigated via Monte Carlo simulation. Since this discharge has a high degree of ionization (>1%), a self consistent simulation of the plasma dynamics is required. The time averaged, spatially dependent electron energy distribution (EED) is computed self consistently by integrating electron trajectories subjected to microwave fields and the space charge field (included by the pondermotive force and the grad-B, $-\mu\nabla_{//}B$, forces and the sheath), and taking into account electron-electron collisions and collisions with hydrogen atoms. At low pressures (~0.5 mTorr), the temperature of the tail portion of the EED exceeds 35 eV, and the sheath potential is -177 V. These results, which are about 70% higher than the previous ones (for the TM_{01} mode), suggests that the TM_{11} mode is more effective than the TM_{01} mode for ECR interaction. A description of the work is provided in the appendix.

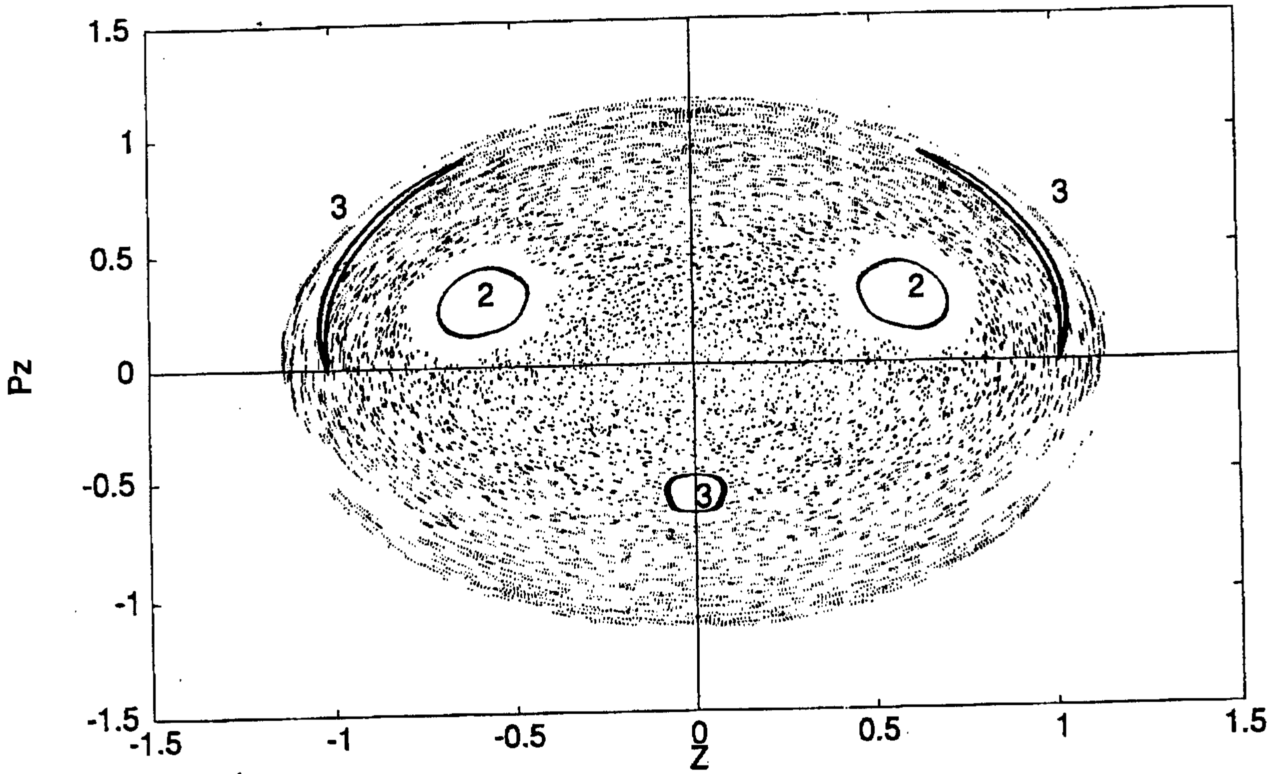

Figure 6: Surface of section at Q=0, for P>0, with period 2 and 3 oscillations marked.

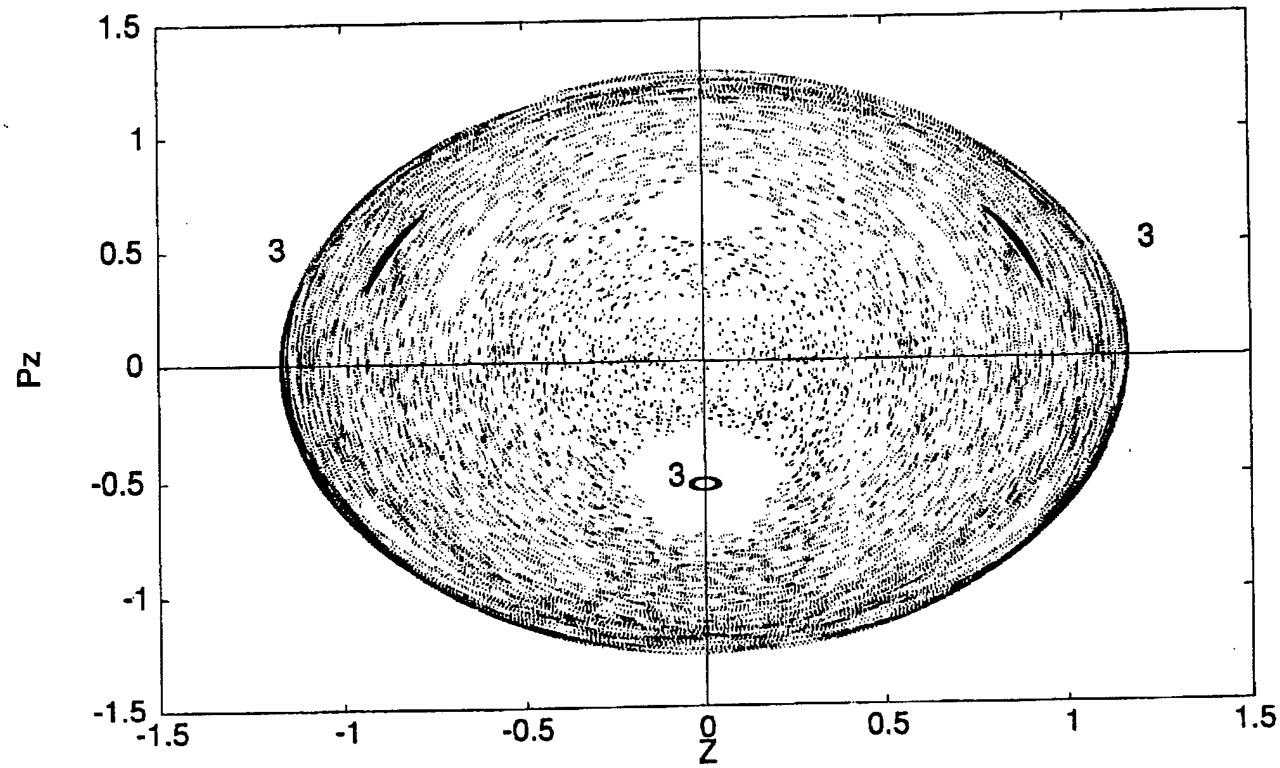

Figure 7: Surface of section at Q=0, for P<0, with a period 3 oscillation marked.

III. Publications

The following publications include works supported by the AFOSR Grant, which was duly acknowledged.

A Journal articles:

1. S. C. Kuo and S. P. Kuo, "Monte Carlo Simulation of Electron Behavior in an Electron Cyclotron Resonance Microwave Discharge using circular TM_{11} Mode Fields", J. Appl. Phys., 80(4), 2512-2514, 1996.

2. S. P. Kuo, "The role of Nonlinear Beating Current, on Parametric Instabilities in Magnetoplasmas", Phys. of Plasmas, 3(11), 3957-3965,1996.

3. James Faith, S. P. Kuo, and J. Huang, "Chaotic Electron Motion Driven by Whistler Waves in the Magnetosphere", Comm. Plasma Phys. Controlled Fusion, 17(3), 173-182, 1996.

4. James Faith, S. P. Kuo, and Joe Huang, "Frequency Downshifting and Trapping of an EM Wave by a Rapidly created Spatially Periodic Plasma", Phys. Rev.B., 55(2), 1843-1851, 1997.

5. James Faith, S. P. Kuo, and J. Huang, "Electron Precipitation caused by Chaotic Motion in the Magnetosphere due to large Amplitude Whistler Waves", J. Geophys Res., 102(A2), 2237-2241, 1997.

6. G. Schmidt, S. P. Kuo, and J. Faith, "EM Wave Propagation in a plasma with Time Dependent Density", Comm. Plasma Phys. Controlled Fusion, accepted for publication, 1997.

7. J. Faith, S. P. Kuo, J. Huang, and G. Schmidt, "Precipitation of Magnetospheric Electrons caused by Relativistic effect Enhanced Chaotic Motion in the Whistler Wavefield", J. Geophy. Res., accepted for publication, 1997.

B. Conference presentations:

1. J. Huang and S.P. Kuo, "A Macro-Kinetic Description of Parametric Instabilities", ICOPS 1996.

2. R. Lyle, S.P. Kuo, and J. Huang, "The Spectral Effect of the Density Irregularities on the Scintillation Index of Transionospheric Signals", ICOPS 1996.

3. J. Faith, J. Huang, and S.P. Kuo, "Chaotic Precipitation of Relativistic Electrons Driven by Large Amplitude Whistler Waves", ICOPS 1996.

4. J. Kim and S.P. Kuo, "Peniotron Mode Radiation of a 16 Slot Cusptron Oscillator", ICOPS 1996.

5. E. Koretzky, S.C. Kuo, and S.P. Kuo, "A Microwave Plasma System for the Deposition of Diamond Films", ICOPS 1996.

6. E. Koretzky, S.C. Kuo, and S.P. Kuo, "Monte Carlo Simulation and Experimental Study of an Electron Cyclotron Resonance Plasma for Thin Film Deposition", ICOPS 1996.

7. J. Faith, J. Huang, S.P. Kuo, "Experimental and Numerical Study of Electromagnetic Wave Trapping in a Time-Varying Periodic Plasma", ICOPS 1996.

8. E. Koretzky, S.C. Kuo, and S.P. Kuo, "An ECR Microwave Plasma Source for Diamond Thin Film Deposition", APS DPP 1996.

9. J. Faith, S.P. Kuo, and J. Huang, "Frequency Downshifting and Trapping of an Electromagnetic Wave by a Rapidly Created Spatially Periodic Plasma", APS DPP 1996.

10. J. Faith, S.P. Kuo, J. Huang, and G. Schmidt, "Precipitation of Magnetosphere Electrons Caused by Relativistic Effect Enhanced Chaotic Motion in the Whistler Wave Fields", APS DPP 1996.

11. S.P. Kuo and J. Huang, “Filamentation Instability of Upper Hybrid Wave in Magneto Plasma”, APS DPP 1996.